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Evaluating the thermal performance of tank cannon components, such as thermal shrouds, muzzle reference system collimators, barrel paint, or thermal signature, by means of firing live ammunition has distinct drawbacks. Not only is range time uncertain, labor and ammunition expensive, but firing must be done outdoors, where uncontrollable environmental factors (such as sunlight, precipitation, and wind) may complicate the analysis and make experimental repeatability difficult. This report will discuss non-firing test alternatives, using various laboratory heating devices, to input heat to the barrel and its accessories in a controllable and repeatable fashion.

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List of Figures

I. Introduction

From experimental evidence, gathered over a 6-fold range of calibers, it has been shown (Brosseau[1]) that the majority of firing generated heat is input to the gun barrel in less than 10^{-1} *sec* (100 *msec*). From the work of Brosseau[1,2] and others,[3,4] it can also be shown that over this 100 *msec* time interval the average heat flux for small (5.56-*mm*) and large caliber (120-*mm*) guns is 10^6-10^7 W/m^2.

In addition to firing, sunlight can add heat to the barrel. Though solar heat flux is far less intense, 10^2-10^3 W/m^2, exposure times are a great deal longer. For example, after a time interval of 10^3 *sec* ($\approx$15 *min*), the net heat input from sunlight can approach that from firing a round.

The primary thermal effects of interest for tank guns are thermal distortion of the barrel, which affects tank gun accuracy and therefore lethality; and thermal signature, which affects vulnerability. This report will discuss ways to simulate environmental and live fire thermal distortion effects.

As the barrel temperature elevates, thermal expansion will lengthen and radially expand the barrel. However, these thermal changes will not adversely affect tank gun accuracy. On the other hand, cross-barrel temperature differences caused by uneven heating or cooling will lead to the type of thermal distortion that degrades accuracy.

Historically, the first recognized source of gun barrel distortion was uni-directional sunlight. The dramatic effect which sunlight has on "fall-of-shot" was demonstrated by Minor et al.,[5] see Fig. 1a, for an uncovered 105-*mm* M68 tank gun barrel. Thermal jackets/shrouds for tank cannon were originally designed for the sole purpose of mitigating this particularly problem,[5-7] as exemplified in Fig. 1b.

Cross-barrel temperature differences can also be caused by uneven heating of the barrel during firing. Manaker and Crouteau[7] (1976) chronicled a number of tests in the early 1970's which found cross-barrel temperature differences to vary in sign and magnitude along the M68 barrel. Similar cross-barrel temperature gradients were found[8,9] across the 120-*mm* M256 barrel, e.g. Figs. 2 and 3. In fact, it can be reasoned that these

[1] Brosseau, T.L., "An Experimental Method for Accurately Determining the Temperature Distribution and the Heat Transferred in Gun Barrels," BRL-R-1740, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD September 1974 (AD-B0001712).

[2] Brosseau, T.L., Stobie, I.C., Ward, J.R., Geene, R.W., "120mm Gun Heat Input Measurements," ARBRL-TR-02413, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1982 (AD-A118378).

[3] Bannister, E.L., Jones, R.N., Bagwell, D.W., "Heat Transfer, Barrel Temperatures and Thermal Strains in Guns," BRL Report No. 1192, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1963 (AD-404467).

[4] Bundy, M.L., "Gun Barrel Cooling and Thermal Droop Modeling," (To be Published as BRL Report) U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1990.

[5] Minor, T.C., Deas, R.W., Lynn, F.R., "Rational Design of Thermal Jackets for Tank Guns," ARBRL-TR-02247, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1980 (AD-B051586).

[6] D'Andrea, G.D., Cullinan, R., Ferguson, M., Peterson, R., Croteau, P., and Giordano, P., "105mm M68 Thermal Shroud," WVT-7249, U.S. Army Benet Weapons Laboratory, Watervliet, NY, November 1972.

[7] Manaker, Lt.A.M., Croteau, P.J., "Study of Anti-Distortion Jackets," WVT-TR-76028, U.S. Army Benet Weapons Laboratory, Watervliet, NY, July 1976.

[8] Zelik, H.J., "Final Report on Technical Feasibility Test of 120-mm Gun Tube Thermal Shrouds and Muzzle Reference Sensor," Report No. APG-MT-5498, U.S. Army Materiel Testing Directorate, Aberdeen Proving Ground, MD, March 1981.

[9] Bundy, M.L., "Analysis of Thermally Induced Barrel Distortion from Firing," Proceedings of the Fifth U.S. Army Symposium on Gun Dynamics, sponsored by U.S. Army Armament Research, Development and Engineering Center Close Combat Armaments Center, U.S. Army Benet Laboratories, Watervliet, NY, September 1987, pp. 81-94.

temperature differences, which tend to be additive, are responsible for much of the change in muzzle pointing angle which occurs during firing, especially during rapid fire. For example, the left and bottom sides of the barrel are hottest in the test of Fig. 2, thermal expansion would predict the barrel should bend upward and to the right. In fact, the muzzle angle change corresponding to the test of Fig. 2, does indeed show, Fig. 4, that the muzzle bends up and to the right, especially during rapid fire.

Thermal distortion can also be caused by uneven cooling. After a round is fired, barrel heated air rises, the hotter air is less efficient at removing additional heat, and thus the top of the barrel is cooled less than the bottom, leading to thermal droop.[4] The eventual drop below 0.0 *mils* in elevation, after the 16th round in Fig. 4b, is likely caused by convection induced thermal droop between shots; this factor increases with increasing barrel temperature and is expected to dominate at high temperatures.

Uneven cooling is also found to occur within the conventional recoil mount, where the thermal conductivity is higher (and therefore removes more barrel heat) through the lower, load-bearing, barrel-to-mount interface, than through the upper, tolerance separated interface.[10] Asymmetric cooling also occurs at the muzzle, where conduction of heat into the (top mounted) muzzle reference system collimator (MRSC) produces a local cross-barrel temperature difference.[11]

Most of the above referenced thermal distortion studies relied heavily on the use of laboratory simulation to evaluate environmental and live fire barrel heating effects. One of the earliest of these was D'Andrea et al.[6] (1972), who utilized infrared (heat) lamps to create a solar-like environment in which to test both candidate thermal shroud designs, and various surface paints. Figure 5 shows a typical correlation between cross-barrel temperature difference, produced by heat lamps, and muzzle angle change. Adding to the simulation techniques, Manaker and Crouteau[7] (1976) simulated sustained firing by employing a propane gas supplied flame to internally heat the barrel. They also simulated the effect of rain on a hot barrel by using an array of over-the-barrel water spray nozzles, see Fig. 6.

Thermal simulation of firing generated heat was also being done in the mid-1970's at the U.S. Army Materiel Testing Directorate (Aberdeen Proving Ground, MD) by using electrical (tubular element) barrel heaters in the combustion chamber of large caliber guns and mortars. This, facilitated the study of ammunition "cook-off," a procedure still in use, e.g., Horton,[12] see Fig. 7.

The use of heat lamps to simulate sunlight is straightforward and has not been improved upon since the work of D'Andrea et al.;[6] therefore, only a brief discussion of this procedure will be given. However, simulation of barrel heat input from firing has expanded, if not improved, from the decade of the 70's, and will be discussed in more detail.

[10] Bundy, M.L., "Gun Barrel and Mount Distortion from Uneven Heat Conduction," BRL-MR-3839, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1990.

[11] Bundy, M.L., "Thermal Distortion of the M1A1 Muzzle Reference System Collimator (MRSC)," BRL-TR-3107, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, May 1990.

[12] Horton, D.W., "Cook-Off Study, British L119/M760, 105-mm Towed Howitzer," Report No. 85-M-101, U.S. Army Combat Systems Test Activity, Aberdeen Proving Ground, MD, September 1985.

II. Barrel Heating Devices and Their Uses

1. Heat transfer by Radiation and Convection

a. Electrical Heaters

(1) Infrared (Heat) Lamps

A typical solar heat flux on a partly cloudy summer day in the northern hemisphere, is around 700 W/m^2. A similar heat flux can be created in the laboratory with heat lamps. For example, an array of 250 W, 120 V bulbs spaced about 25 cm apart and 10-12 cm off the surface, will produce a heat flux pattern like that shown in Fig. 8, which has an overall surface-average near that sought. More heat lamps, spaced closer together, but farther from the surface will smooth out the intensity variation. For example, Gladstone[13] used 250, 375 W bulbs located 1.5 m ($\approx$5 ft) above a full scale tank, Fig. 9, to create a relatively smooth solar-like heat flux over the tank's upper surface, as shown in Fig. 10.

Heat lamps are the preferred method for simulating external, solar-like heating, but their low wattage and physical size make them less suitable than many other devices for simulating firing-like heat input.

(2) Heating Elements

A typical internal barrel heater, like that used in the cook-off studies of Horton[12], will generate 2.2x10^4 W/m^2 over a length of nearly 2 m. Thus, the heat equivalent of a single round can be input over roughly a third of a typical tank gun barrel in 10^1-10^2 sec. For example, Fig. 11 shows the change in the average barrel temperature at 1 m from the muzzle resulting from the firing of 14 rounds in a period of 8.2 min, versus continuous application of the barrel heater for the same time. The results are quite similar, the average time equivalent of one round being 35 sec.

By moving such a barrel heater back and forth along the bore length a temperature distribution like that which occurs from firing, can be created, e.g., Fig. 12. This procedure was used to study the the vertical cross-barrel temperature difference, and resulting thermal distortion, that developed due to the upward convection of heated air in and around the barrel.[4] This same procedure was used to study the uneven conduction of heat from the barrel to the recoil mount through the lower, load-bearing surfaces.[10]

Continuous operation of electrical barrel heaters may be the preferred method to simulate (over a significant length of the barrel) the average thermal effect of long-term, sustained firing. However, it is not suitable for simulating high rates of fire, or for recreating the temperature spike effect which occurs through the barrel after each round is fired. A combustion-type heater is better adapted for the latter purpose.

[13] Gladstone, D.H., Private Communication, National Defence Headquarters, Ottawa, Canada, April 1990.

b. Combustion Heating

(1) Oxy-Gas Torch

The electrical barrel heater referred to in Fig. 11, can not simulate firing rates above 2 rounds per minute. However, an oxy-gas flame can be used to simulate firing rates at least twice as fast. To demonstrate this, a standard acetylene welding unit was fitted with a so-called "rose bud" torch, which generates a wide flame, see Fig. 13. The energy released in the combustion of one part acetylene and two parts oxygen is 8.5 MJ/m^3, with a flame temperature of 3750 K.[14] Assuming a (typical) flow rate of 3.0 m^3/hr (105 ft^3/hr), yields a heat generation rate of 7000 W. Assuming as well, a flame length of 30-40 cm (see Fig. 13), the average heat influx to the in-bore surface, when the torch is placed in a 120-mm (diameter) barrel, is 4.7-6.3x10^4 W/m^2. This heat flux is 2.1-2.9 times higher than the electrical barrel heater. Experimentally, when the "rose bud" torch was inserted into the muzzle of the 120-mm M256 barrel for 12 sec it produced a barrel temperature rise equivalent to one round, see Fig. 14. The oxy-gas torch can thus be used to simulate a firing rate of 5 rounds per minute, which is $\approx$2.5 times higher than the electrical heater, and falls in the middle of the computed heat flux range. This device was used to test the thermal distortion of the muzzle reference system collimator.[11]

(2) Powder Charge

Though the torch method can input the heat equivalent of one round every 12 sec, this is still more than 100 times slower than that which occurs from live firing. An explosive-type reaction is needed to input the equivalent amount of heat in a shorter time. For example, a 60 g black powder sample, rolled in tissue paper (roughly 20 cm in length), was held in place along the bore axis by a wire-mesh screen. Using an electrical ignition system, the resulting combustion was estimated to take place in less than 100 $msec$, with an average barrel temperature rise similar to that which occurs from firing, Fig. 15. Using this method, the radial temperature gradient from an explosive (firing-like) heat pulse is seen, for example, Fig. 16, to take several minutes to dissipate through a 40 mm thick gun barrel wall.

2. Heat Transfer by Conduction (Through Electrical Heaters)

a. Heating Pad

Another form of electrical heater which can be used to heat the inside bore surface is a heating pad. Unlike the rigid, tubular element heater, the heating pad is placed in direct contact with the barrel surface and therefore uses conduction (versus convection or radiation) as the mode of heat transfer. For example, a commercially fabricated pad was found to produce 7.0x10^3 W/m^2 through each side of a 0.13 m by 0.36 m rectangular surface (the pad was 2 mm thick). Using a thin metal backing plate, of the same dimensions, this pad can be held against the bore surface with split, spring steel rings. A small hole in the center of this pad provides access to the bore surface for a thermocouple to monitor

[14] Morgan, H.P., "Oxyacetylene Welding," published by American Technical Society, Chicago, 1958, p.17.

the barrel temperature. Using a commercially available digital temperature controller, the heating pad can be turned on and off to maintain a pre-set temperature value. This heating device will also operate by clamping it around the outer barrel surface.

Such a small, temperature controlled heating pad (whether internally or externally mounted) can be used to simulate three-dimensional hot spots along the barrel after firing, like those indicated by the cross-barrel temperature differences of Fig. 3. To demonstrate this, a heating pad was externally clamped to the underside of the barrel (centered at about 1.5 *m* from the muzzle), as shown in Fig. 17. After 60 *min* of continuous heating, a cross-barrel temperature difference of more than 40 *K* was established, resulting in a muzzle angle change of 1.3 *milliradians* (*mils*), see Fig. 18.

b. Heating Belt

Similar to the heating pad, a flexible heating belt (also commercially available) can be wrapped around the barrel to create a symmetric heat input to the barrel. This method of heating the barrel may be preferable to the internal, tubular element barrel heater, when the bore needs to remain open, such as when a round is to be fired, or a bore scope inserted.

As an example, a 3.5 *m* (12 *ft*) long, by 5.1 *cm* (2 *in*) wide (6 *mm* thick) heating belt, which outputs 3.4×10^3 W/m^2 through each side, was wrapped around the barrel in the same region as described for the heating pad test of Fig. 17. Though the heat input was considered symmetric, the effects of internal air convection are seen in Fig. 19a to induce a 8 *K* temperature difference between the top and bottom of the barrel, producing a 0.4 *mil* droop of the muzzle angle after 30 minutes, Fig. 19b.

III. SUMMARY

There are several non-firing methods which can be used to create firing-like barrel heat input. The heating devices vary in intensity from heating pads and belts, which output 10^3-10^4 W/m^2; to solid element electrical heaters, and oxy-gas torches, which output 10^4-10^5 W/m^2; to powder charges, which (like the actual firing event) output 10^6-10^7 W/m^2 over roughly a 100 *msec* time interval.

The techniques described herein, allow almost any firing produced barrel temperature condition to be duplicated. These non-firing procedures provide an opportunity to study – at length – the origins of many thermal distortion effects in the tank gun system. Future work in the area of thermal signature, and barrel cooling techniques, will undoubtedly utilize and expand upon many of these barrel heating devices and procedures.

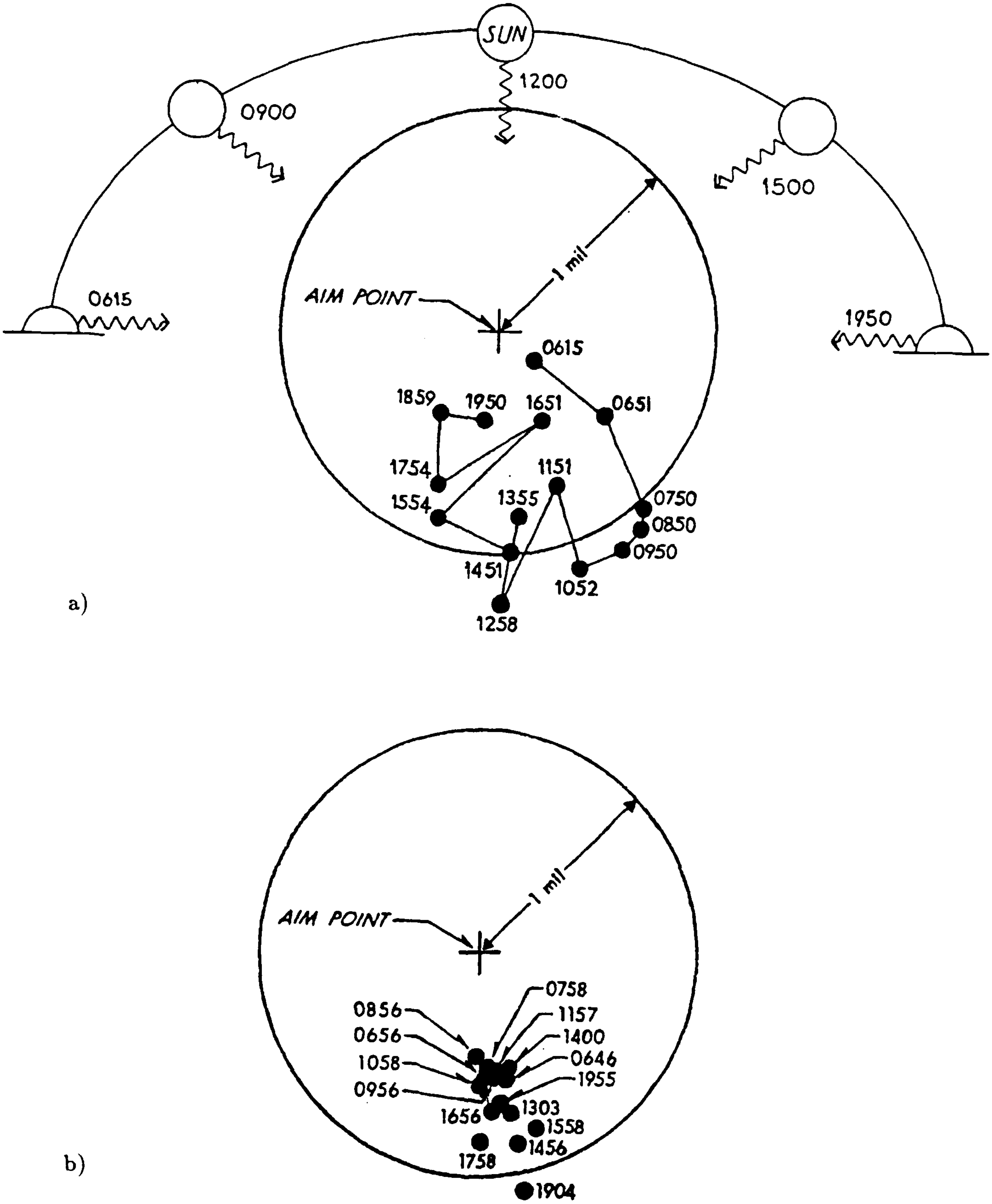


Figure 1. The Effect of Sunlight on "Fall-of-Shot" for a) an Unshrouded, and b) a Shrouded, M68 Gun Barrel, from Ref. 5.

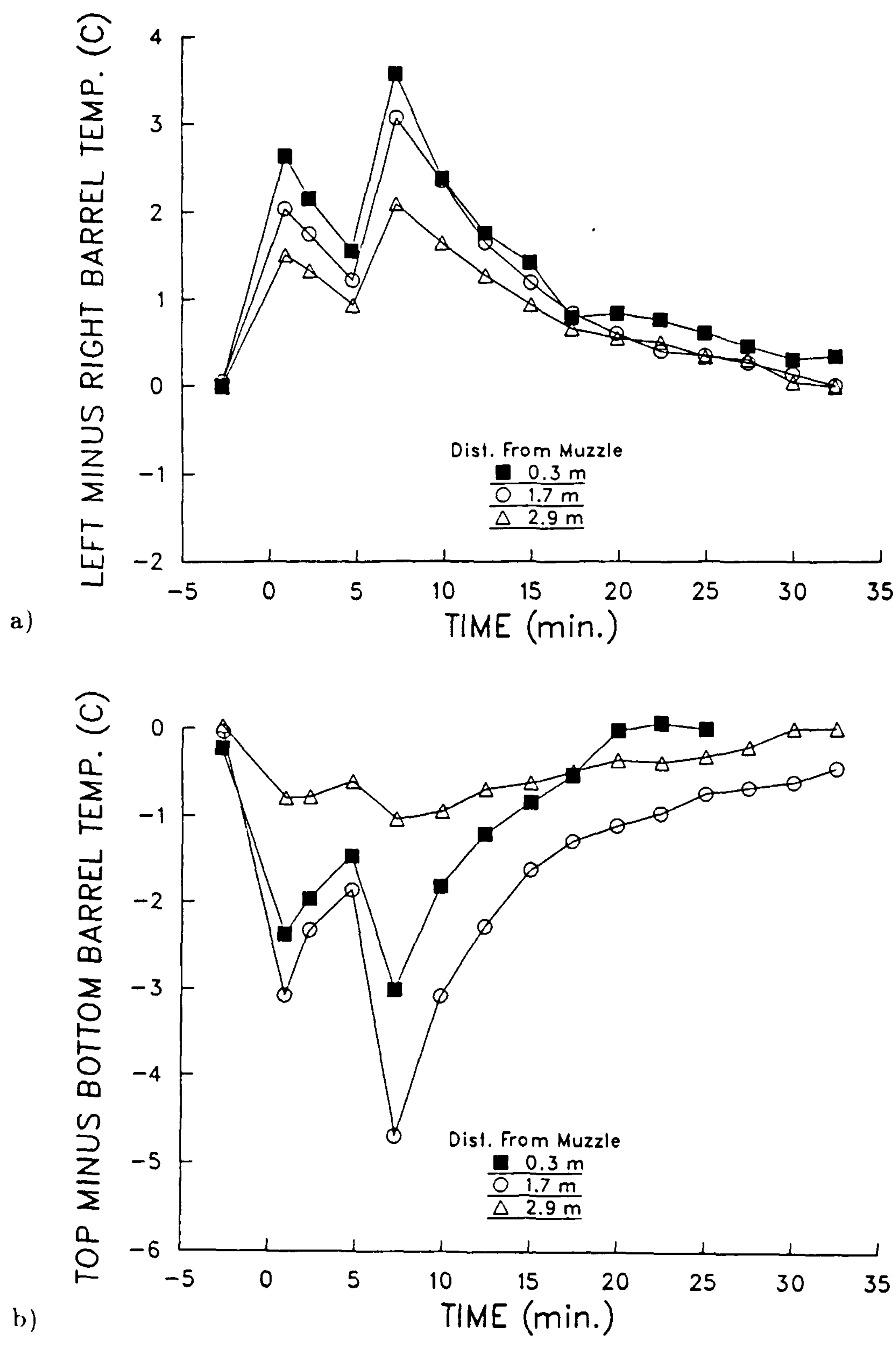


Figure 2. Cross-Barrel Temperature Difference Across an Unshrouded M256 Gun Barrel in: a) the Azimuthal Plane, and b) the Elevation Plane; for Two Consecutive Rounds, from Ref. 8.

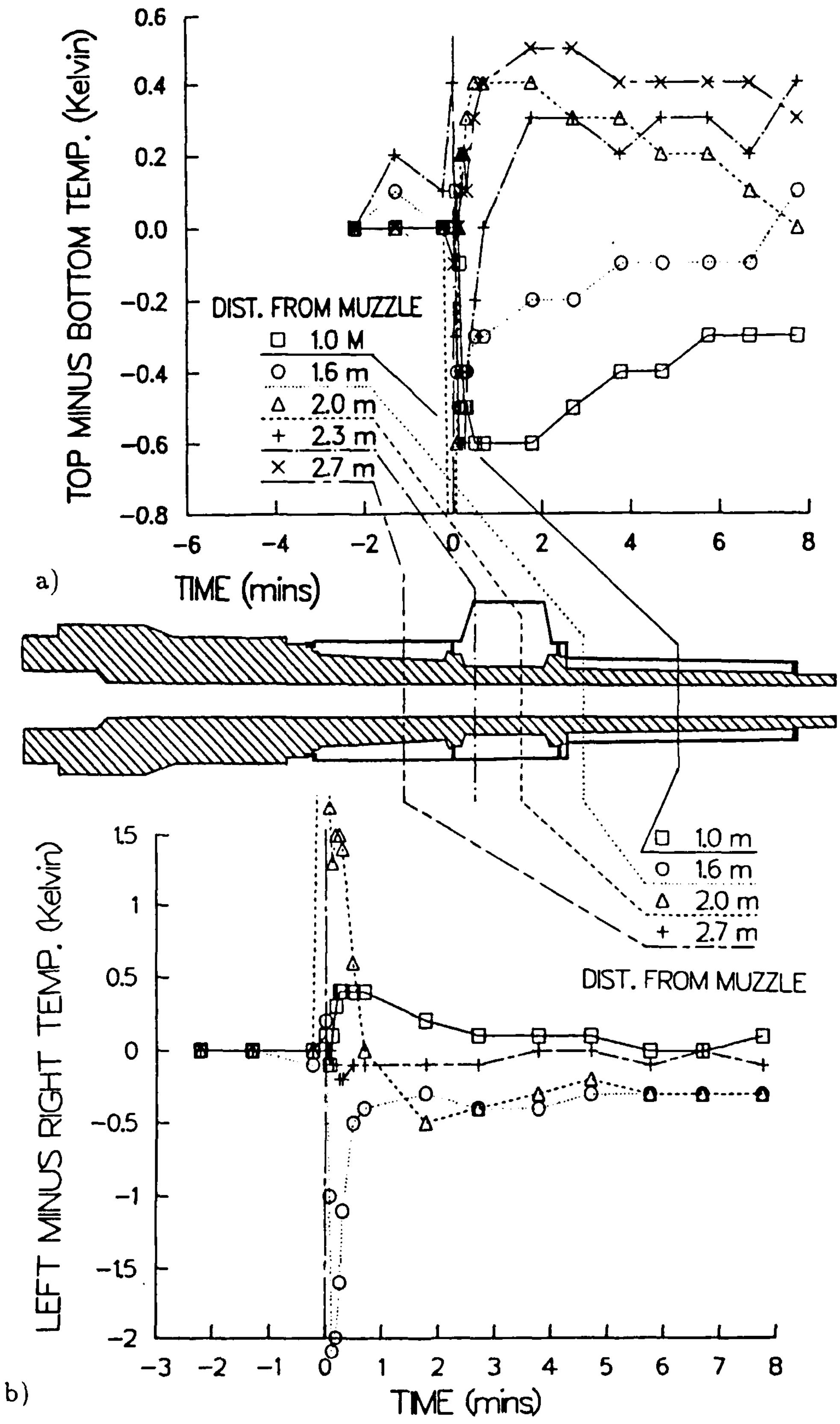


Figure 3. Cross-Barrel Temperature Differences along a Shrouded M256 Gun Barrel in: a) the Elevation Plane, and b) the Azimuthal Plane; for a Single Round, from Ref. 9.

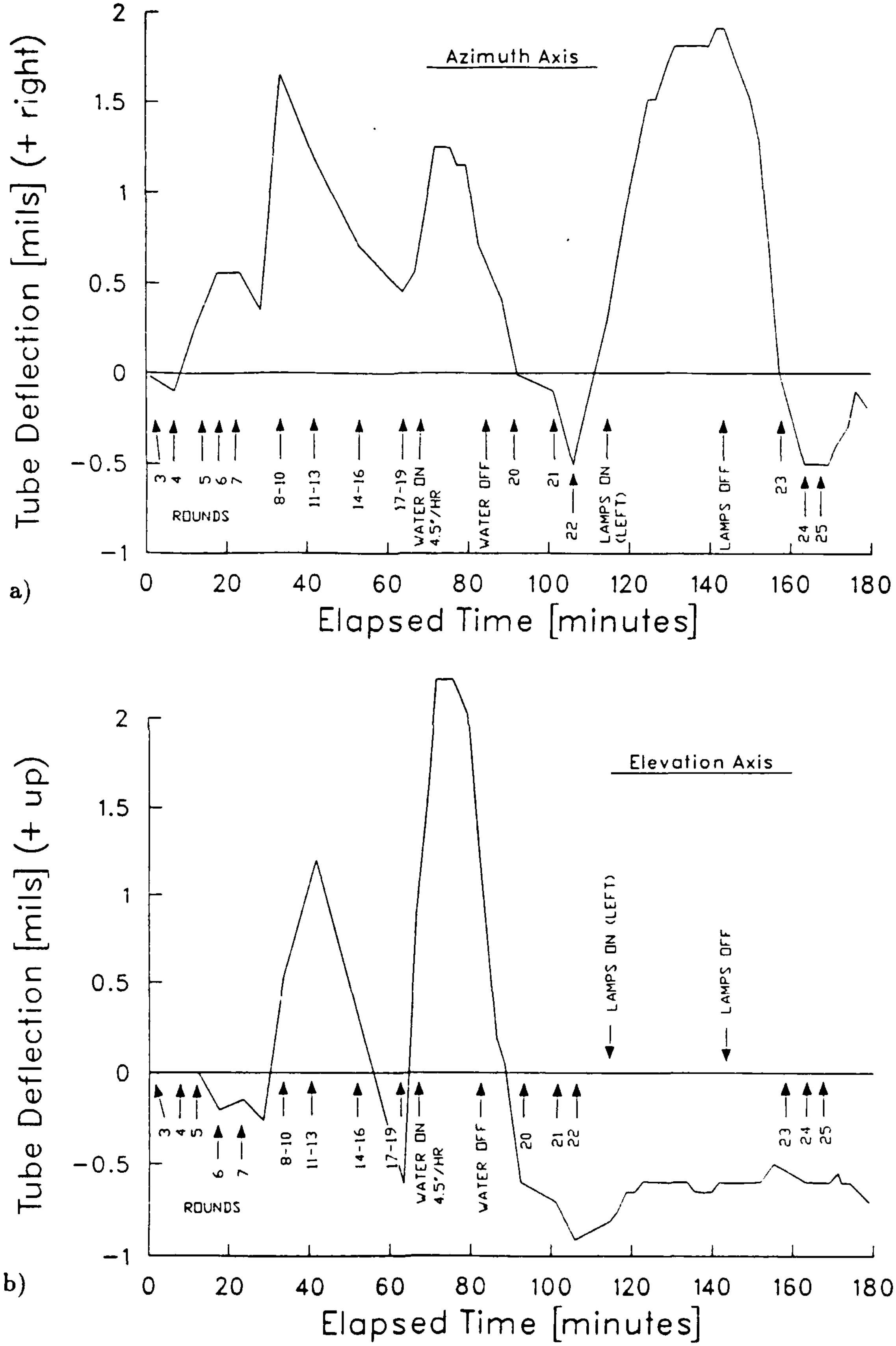


Figure 4. Muzzle Angle Variation (in *Milliradians*, *Mils*) in a) the Azimuthal Plane and b) the Elevation Plane During Firing, from Ref. 8.

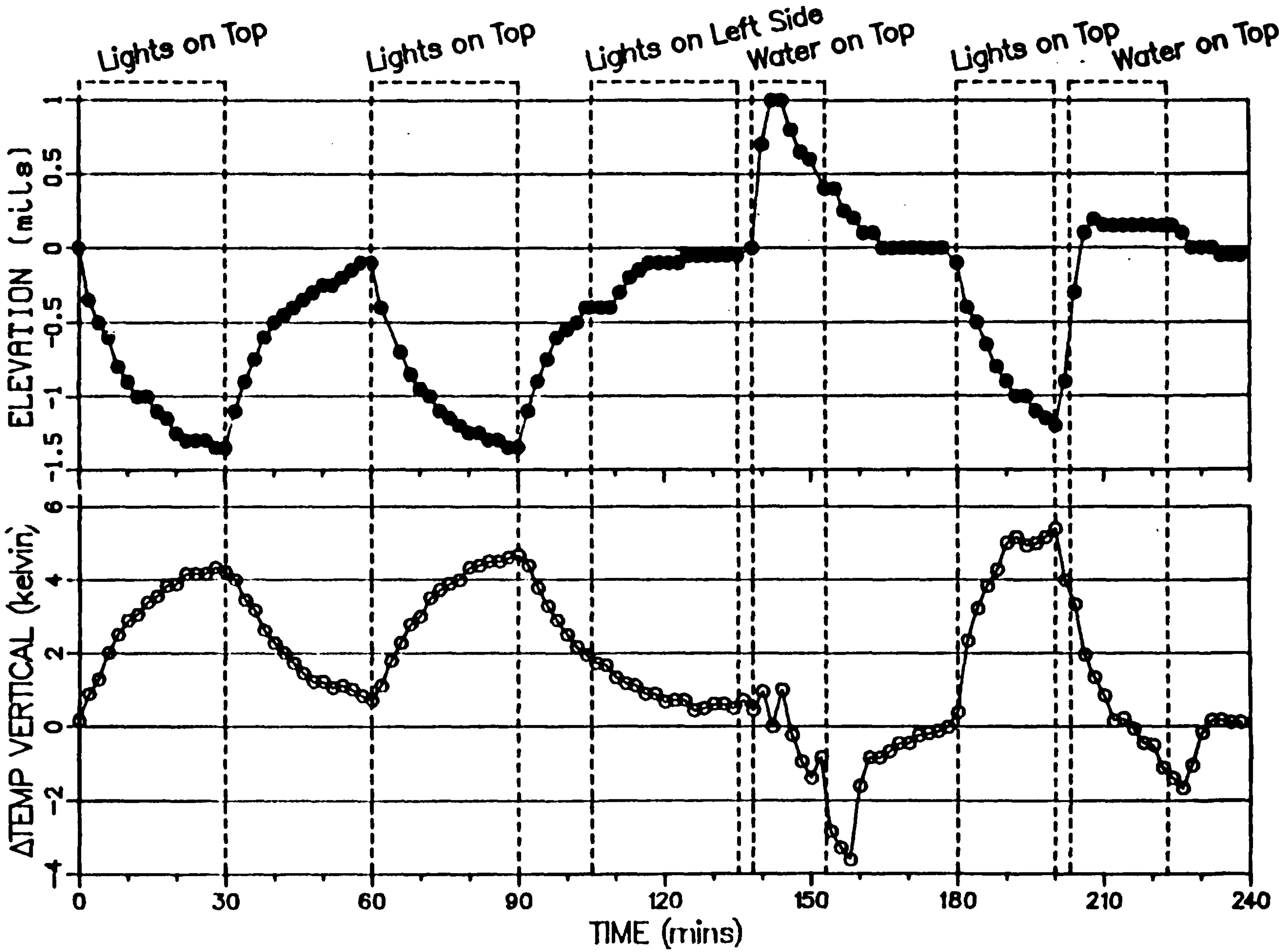


Figure 5. Typical Correlation Between Cross-Barrel Temperature Difference, Produced by Infrared Lamps, and Muzzle Angle Deflection.

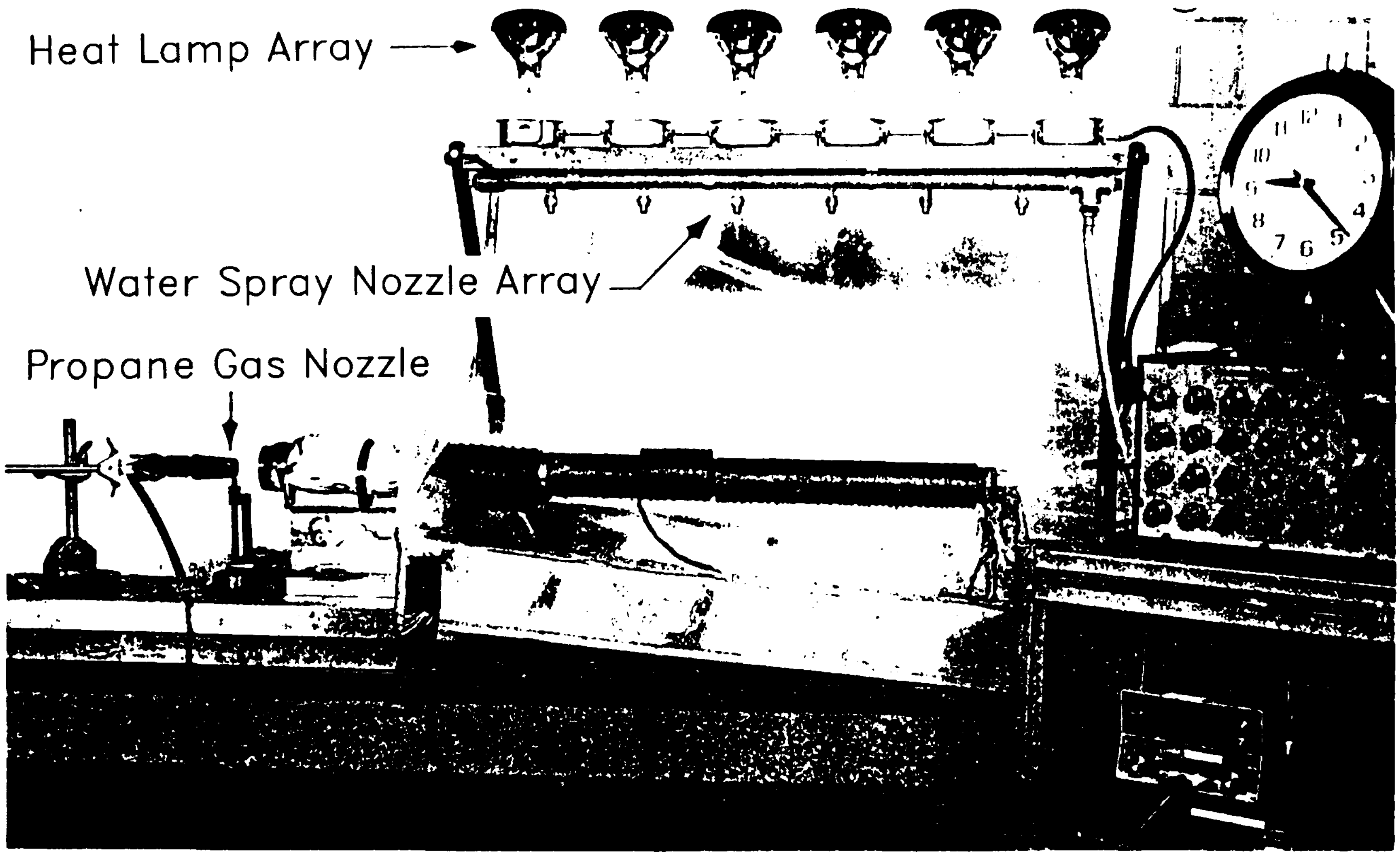
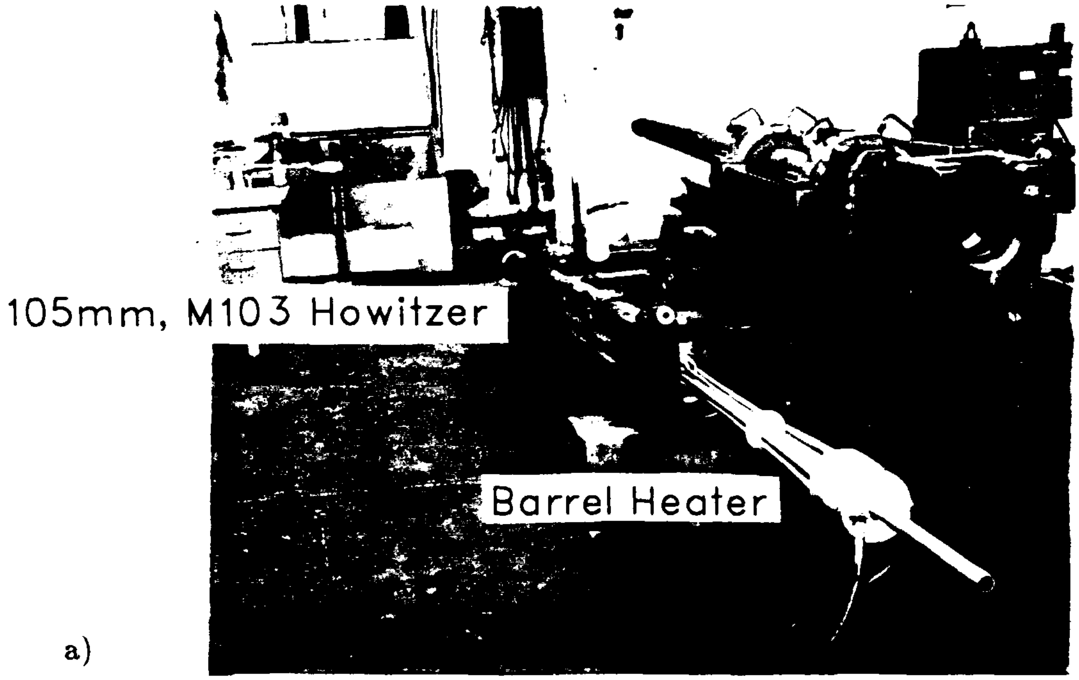


Figure 6. Experimental Set-Up for Simulating the Thermal Effects Produced by Sunlight, Rain, and Firing on a Scale Model M68 Gun Barrel, from Ref. 7.



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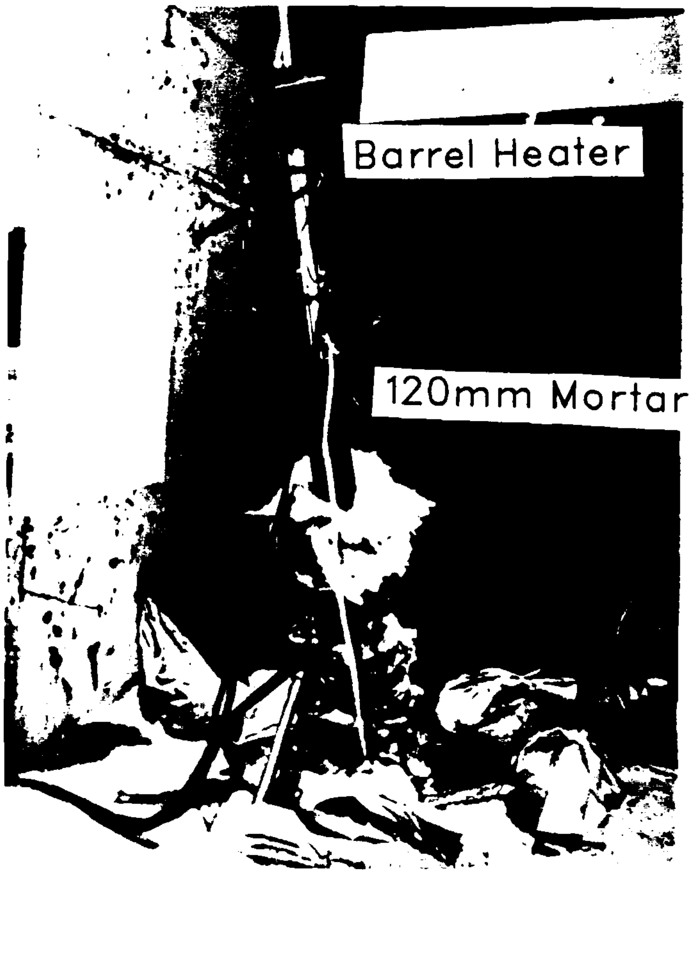

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Figure 7. Internal, Electrical Barrel Heaters Used to Study Ammunition "Cook-Off" in: a) 105 – *mm* Howitzer; and b) 120 – *mm* Mortar, Courtesy of Horton (Ref. 12).

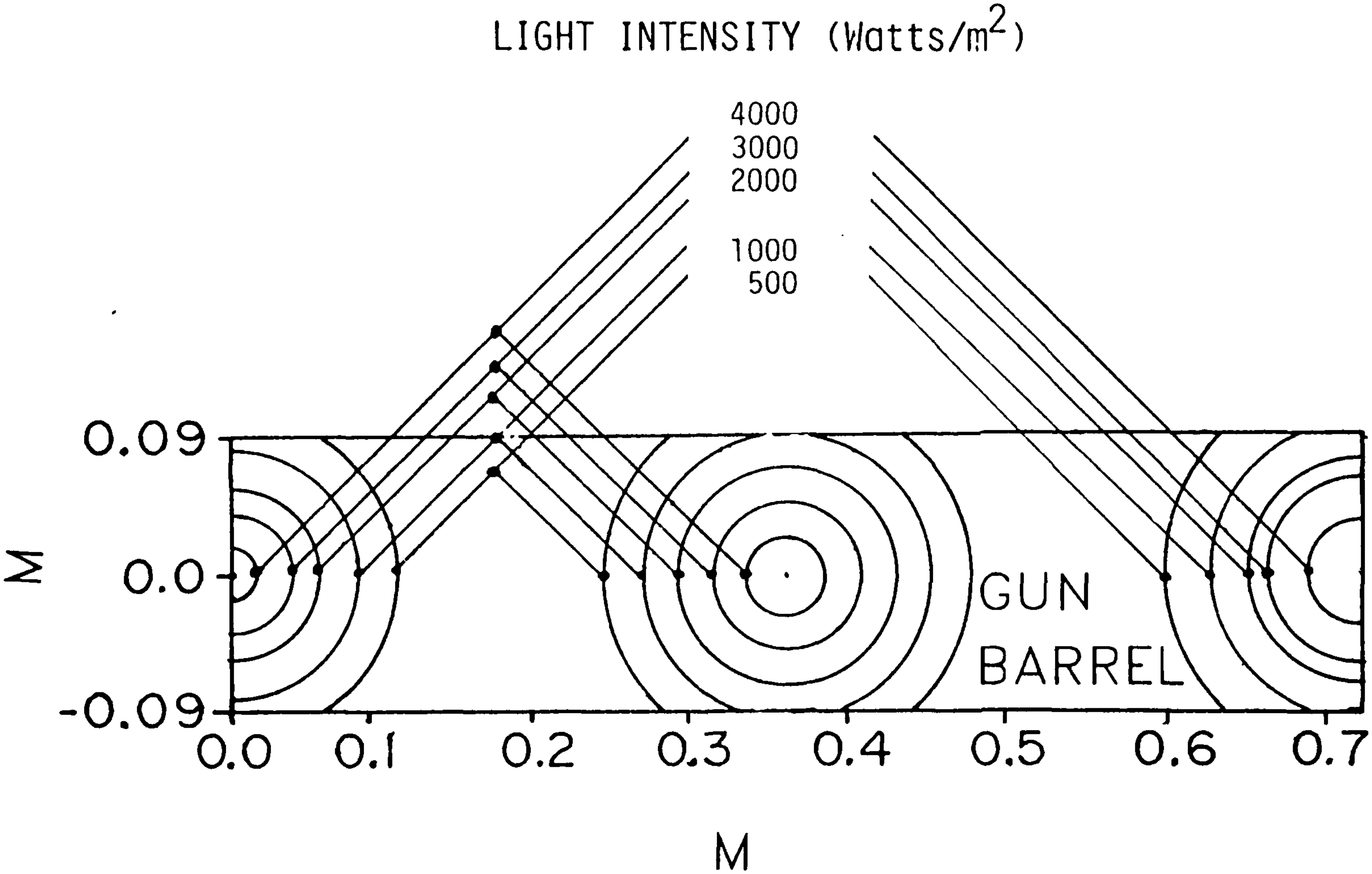


Figure 8. Heat Flux Profile 10-12 *cm* Below Overhead Array of 250 *W* Heat Lamps.

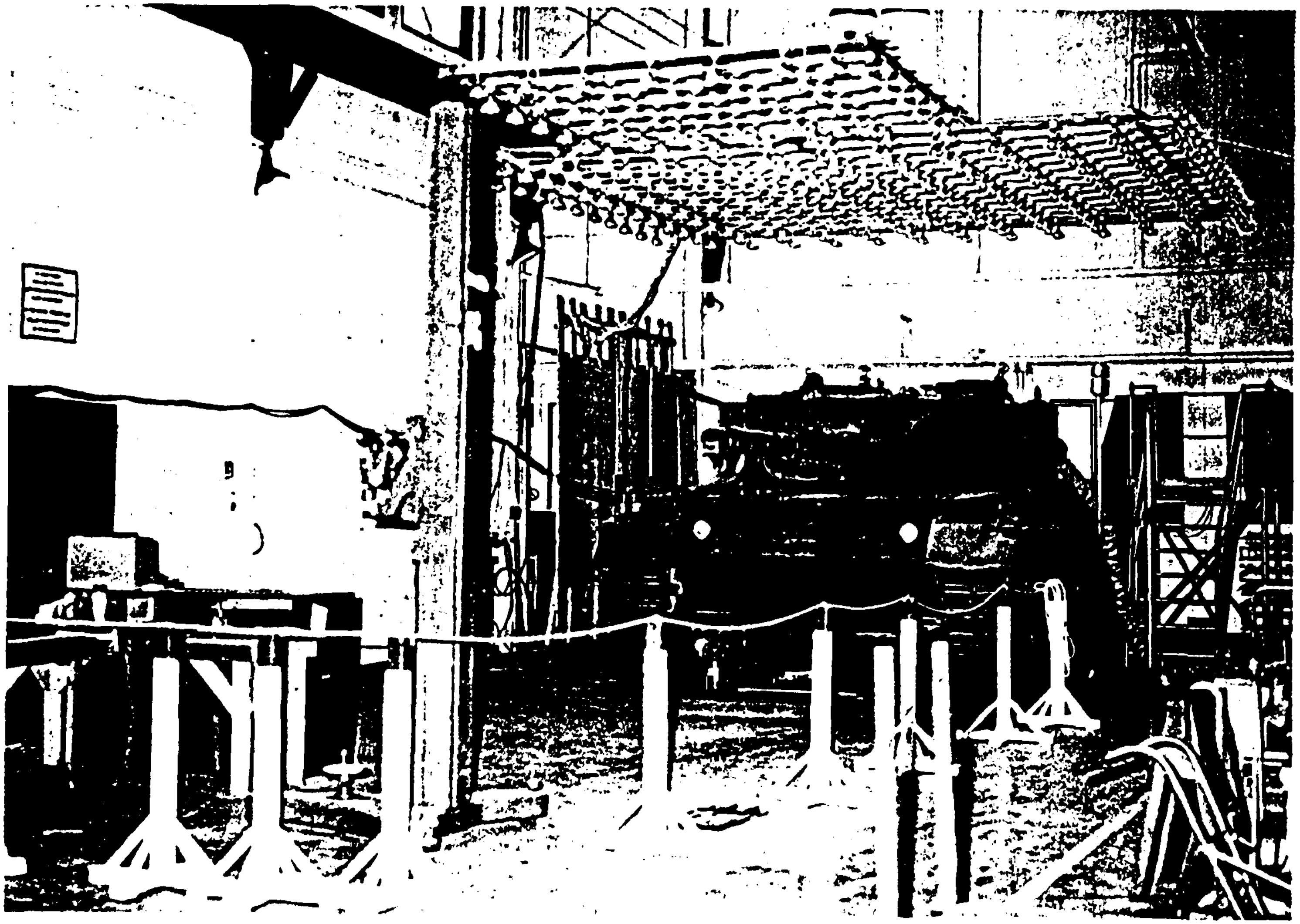


Figure 9. Two-Dimensional Array of Overhead Heat Lamps to Simulate Solar Radiation on Full Scale Tank, Courtesy of Gladstone (Ref. 13).

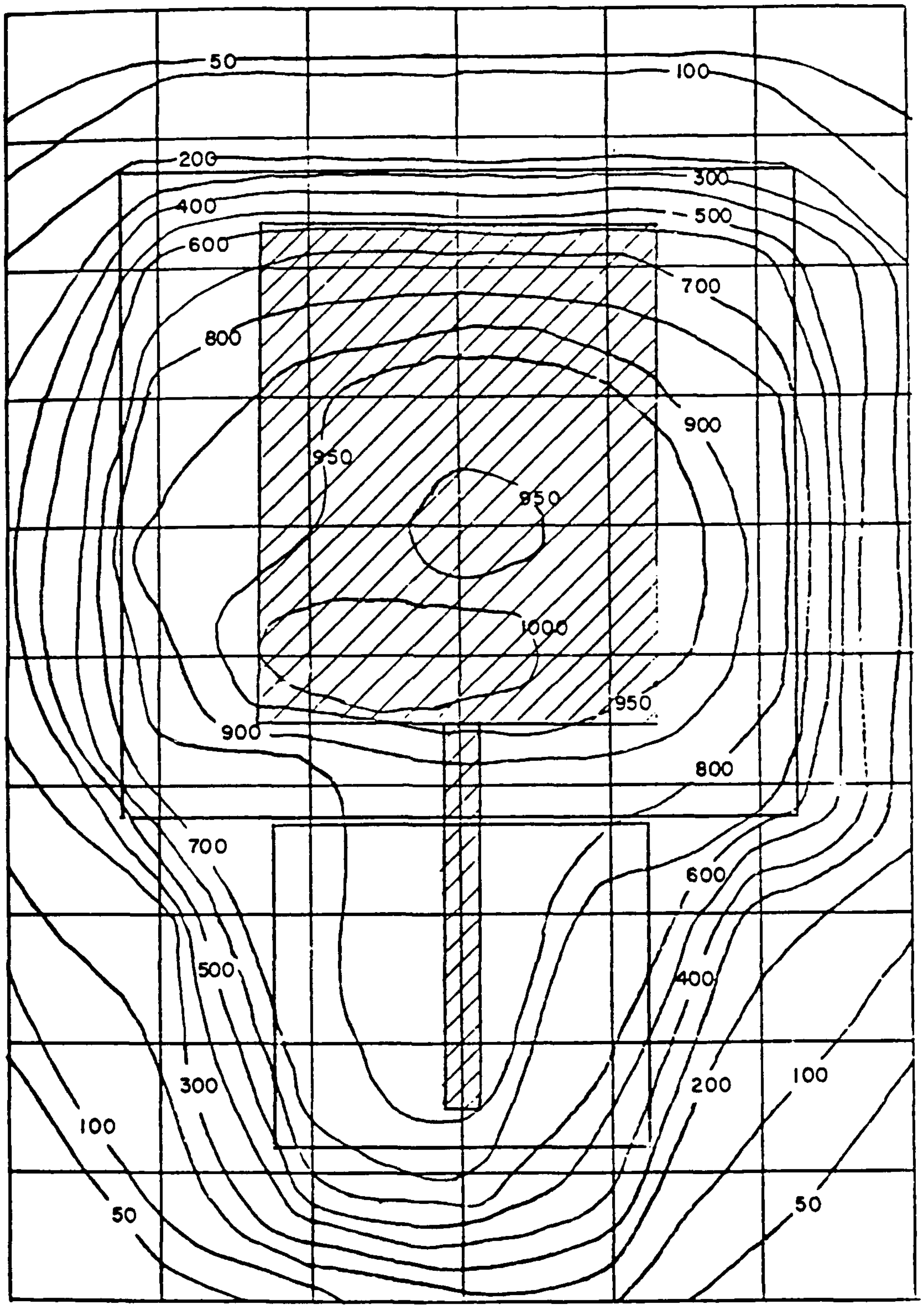


Figure 10. Heat Flux Profile ≈ 1.5 m Below 250, 375 W Heat Lamps (see Fig. 9), Courtesy of Gladstone (Ref. 13).

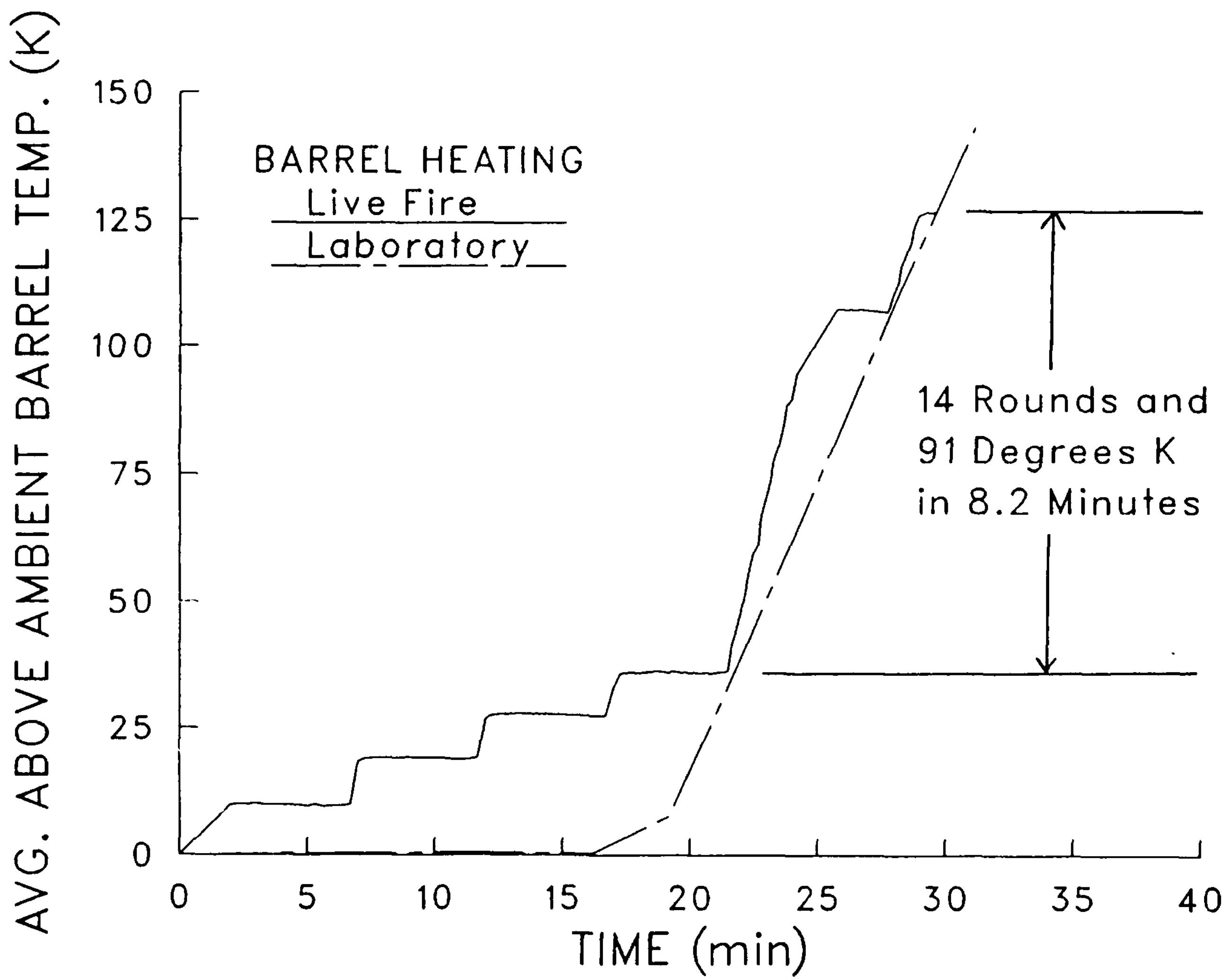


Figure 11. Comparison of Barrel Temperature Increase from Firing (at 1.0 m from the Muzzle), with that Produced by Internal Barrel Heater.

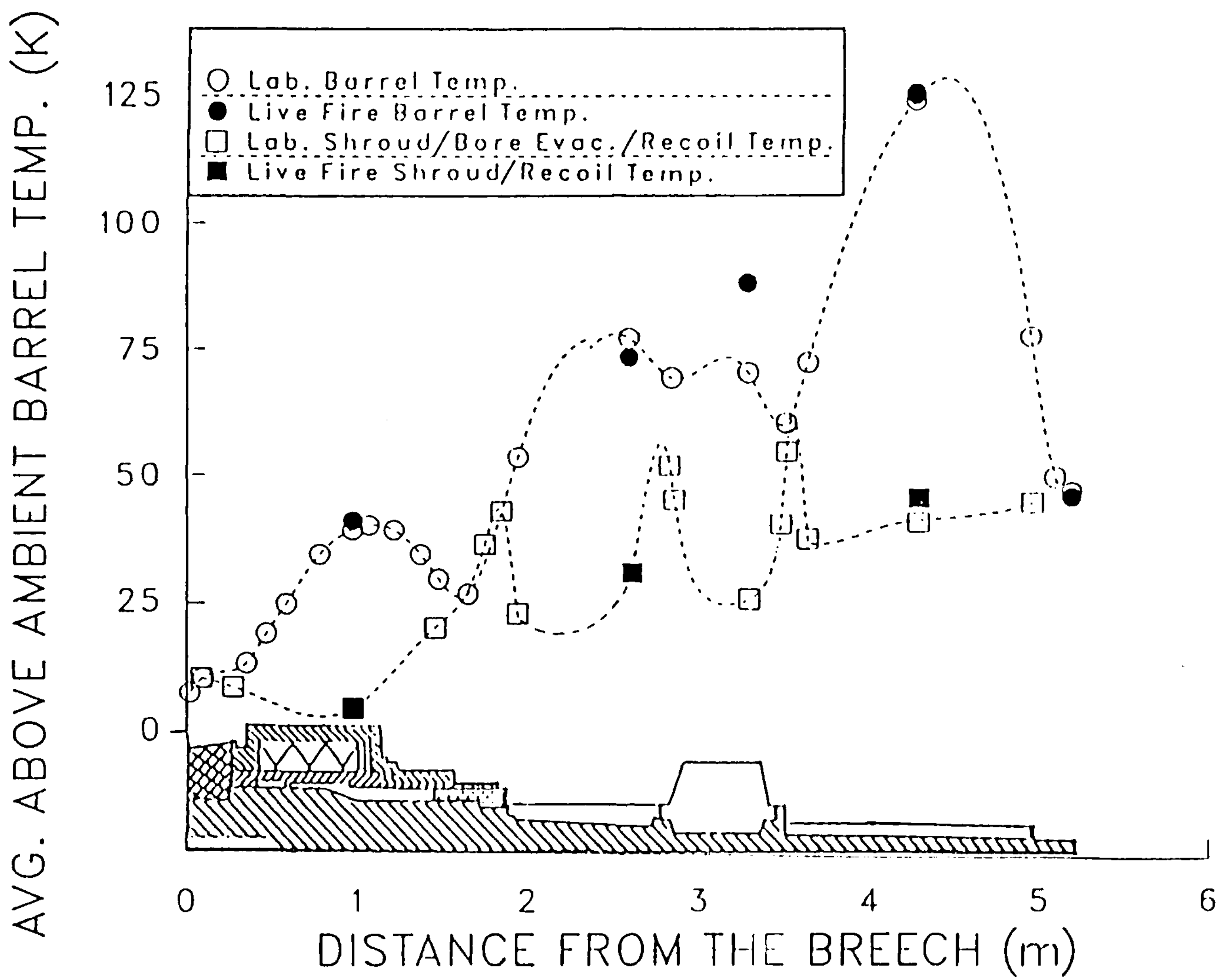


Figure 12. Comparison of Barrel Temperature Distribution Created by Firing (at the rate of $\approx$1 Round/10-15 *min*), with that Produced by Internal Barrel Heater.

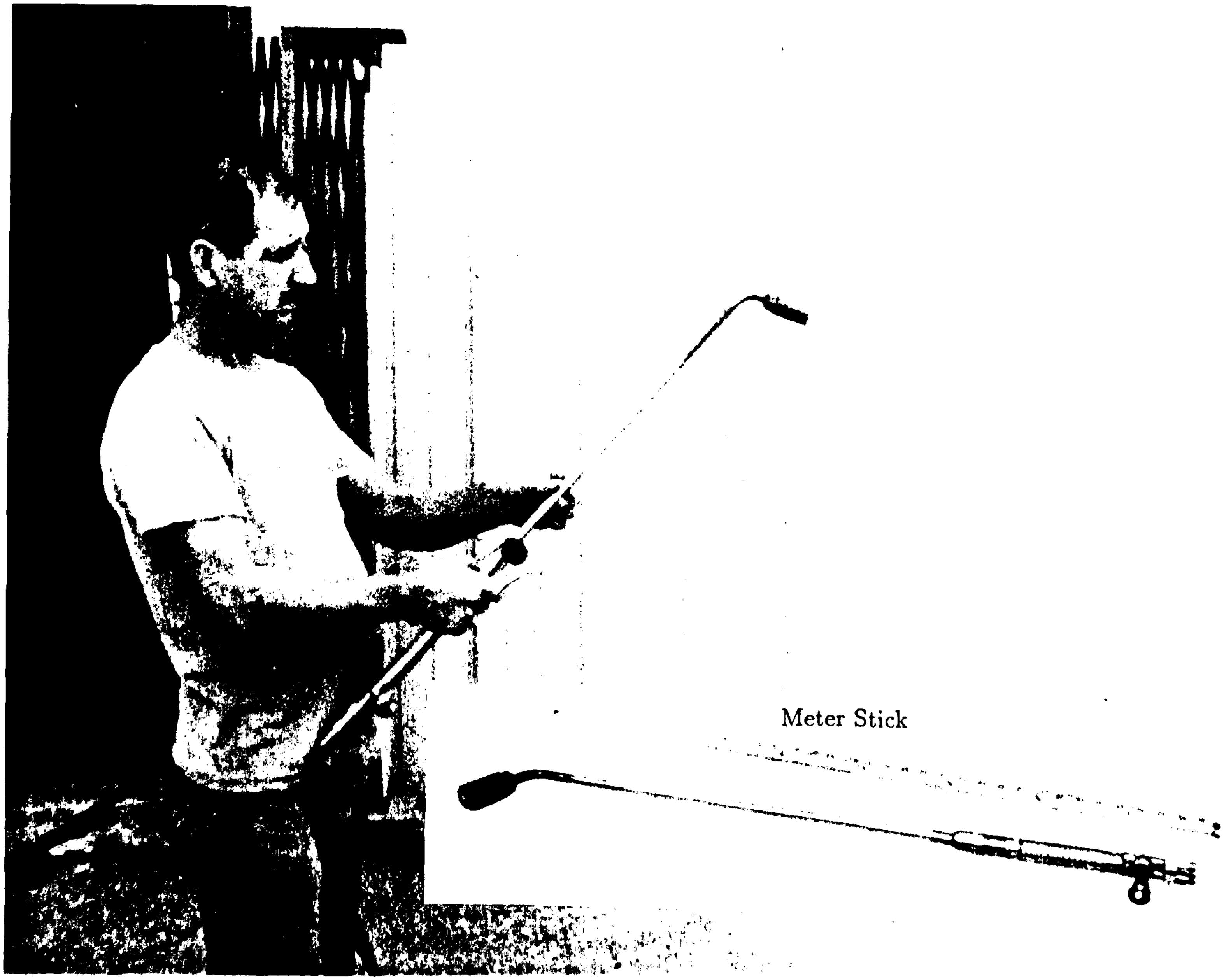


Figure 13. View of "Rose Bud" Torch Used to Provide Firing-Like Heat Input to the Barrel.

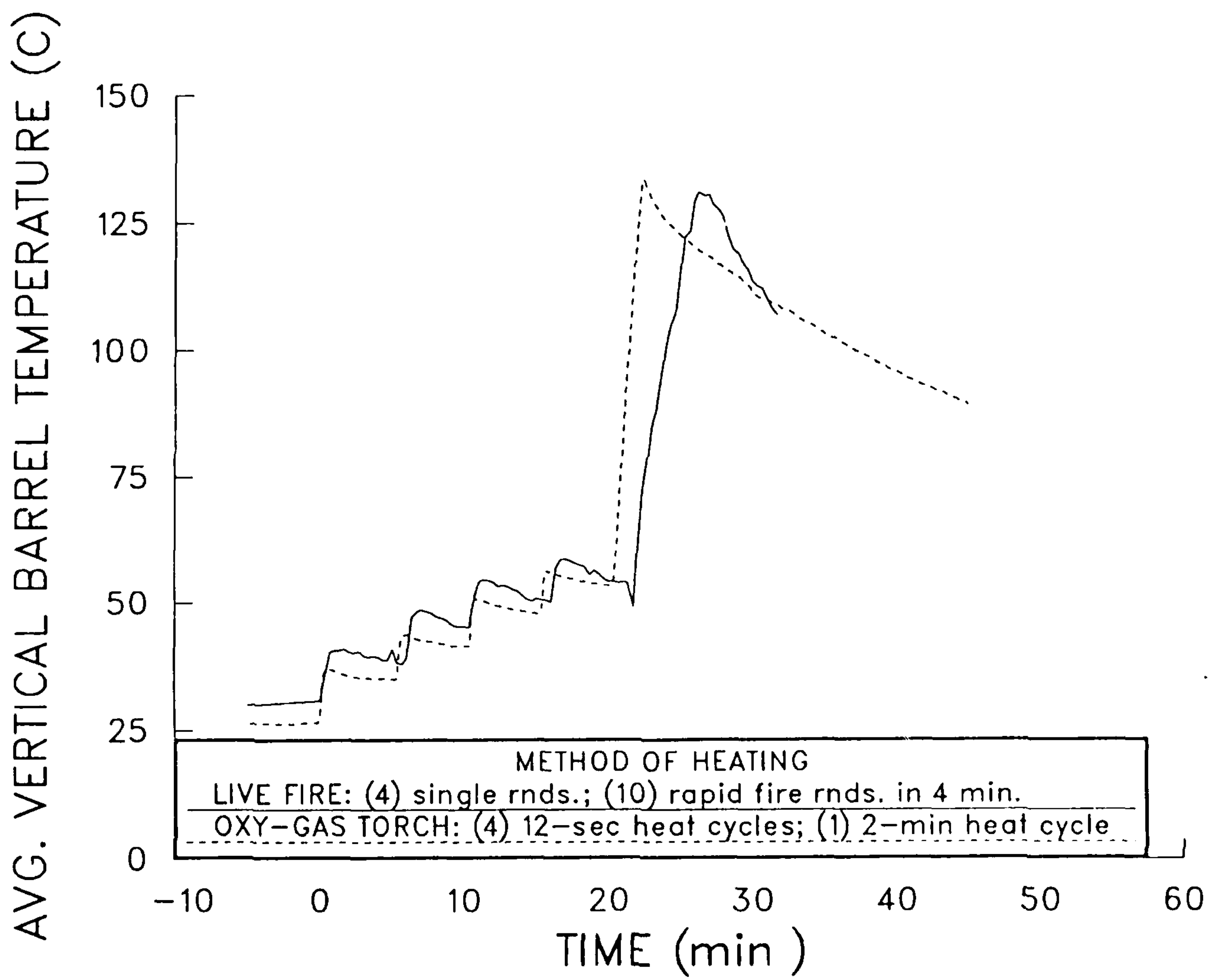


Figure 14. Comparison of Barrel Temperature Increase from Firing (at 0.1 m from the Muzzle), with that Produced by Oxy-Gas Torch of Fig. 13.

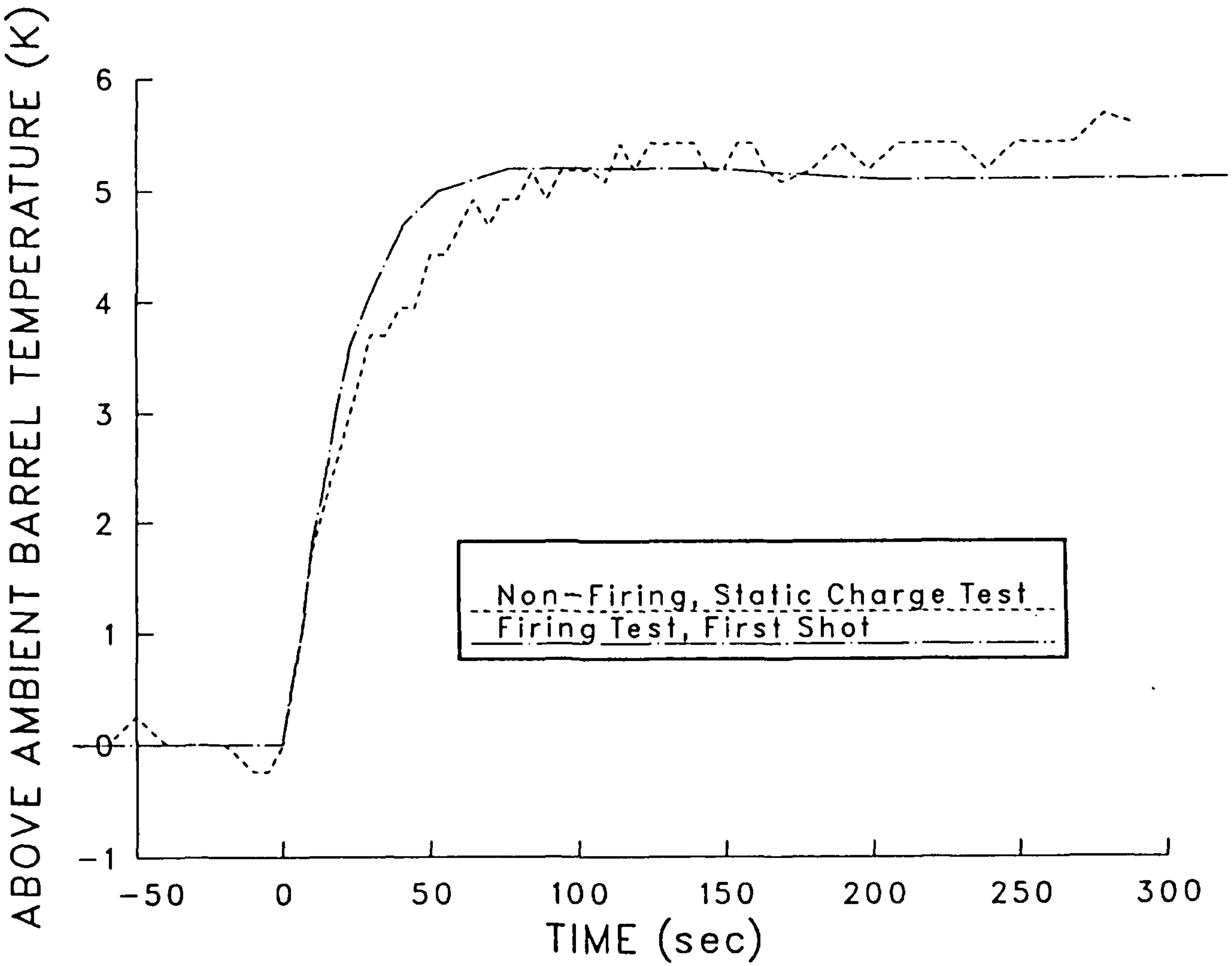


Figure 15. Comparison of Barrel Temperature Increase from Firing (at 2.7 m from the Muzzle), with that Produced by a 60 g Black Powder Charge.

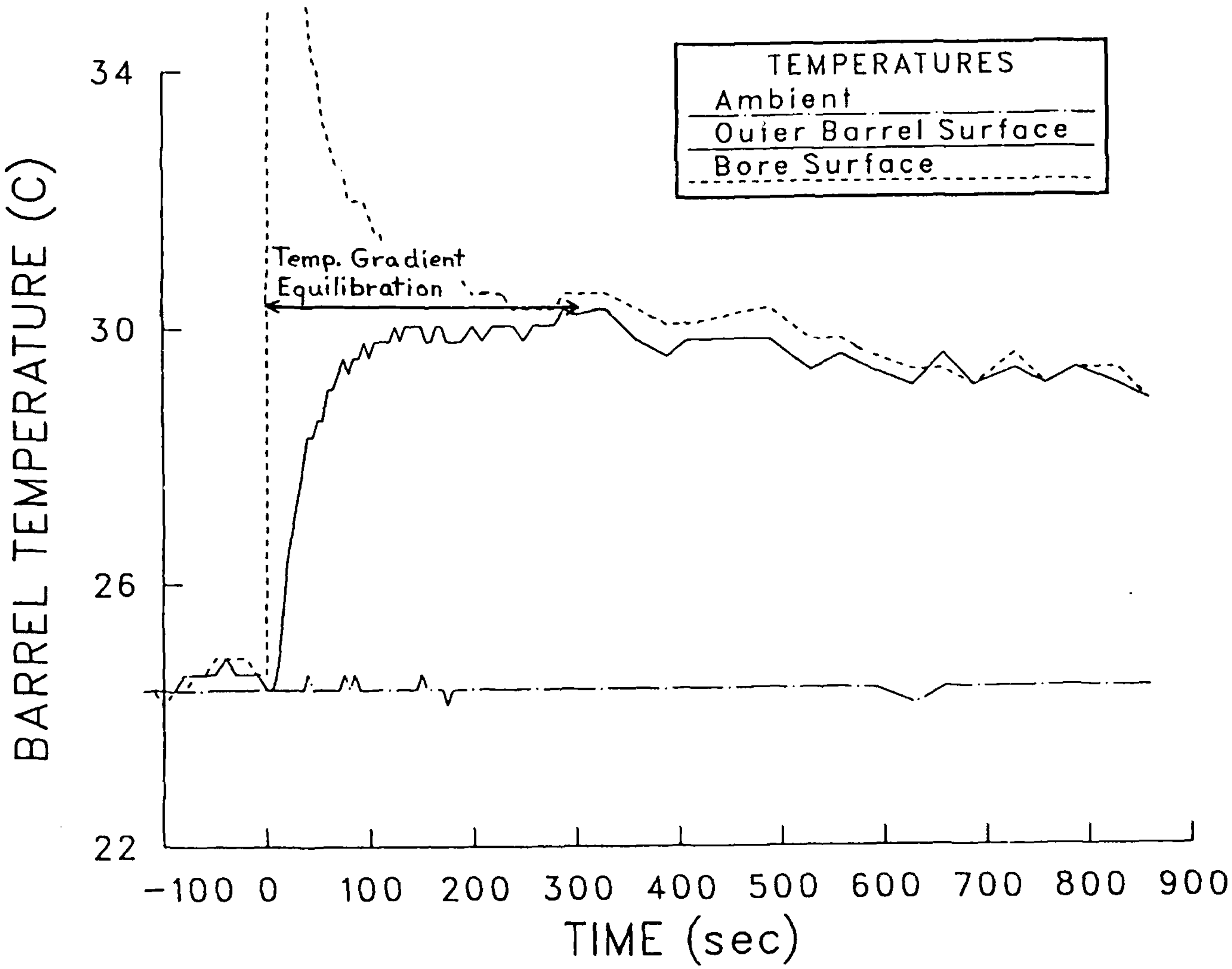


Figure 16. Inner and Outer Barrel Wall Temperature Versus Time After Ignition of 60 g Black Powder Charge.

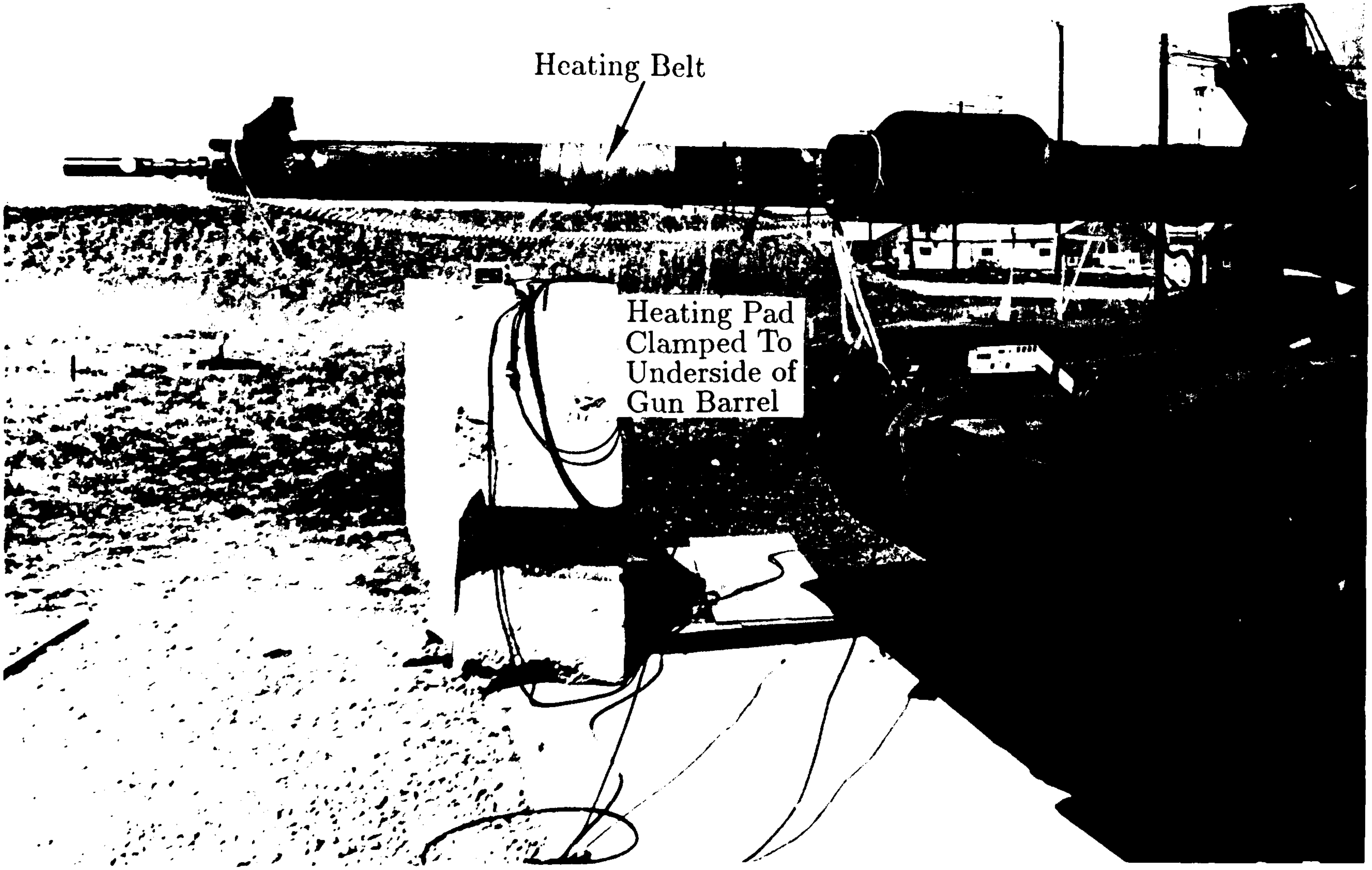
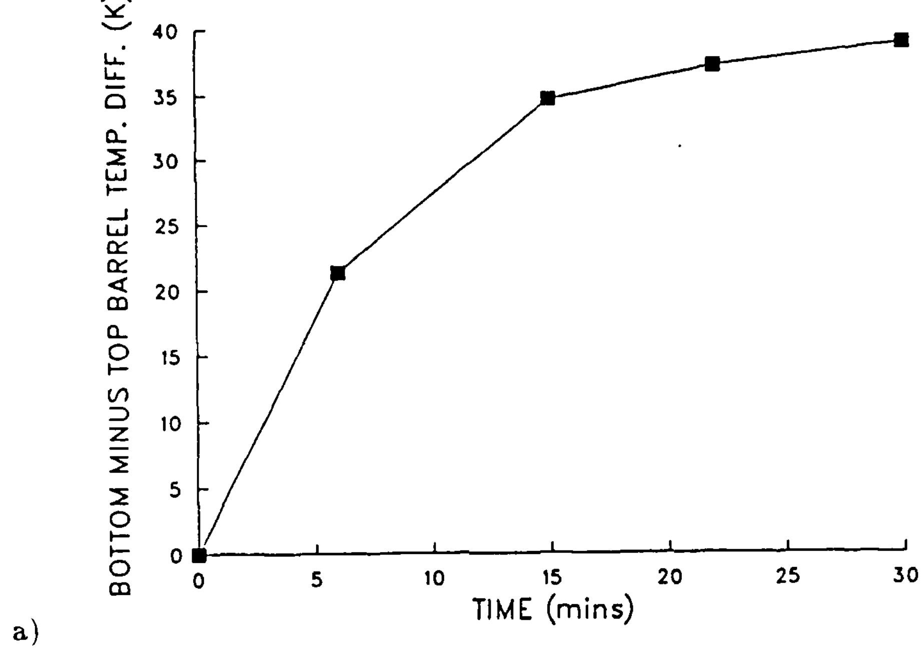


Figure 17. Creating Asymmetric and Symmetric Barrel Heat Input Using a Heating Pad and a Heating Belt, Respectively.



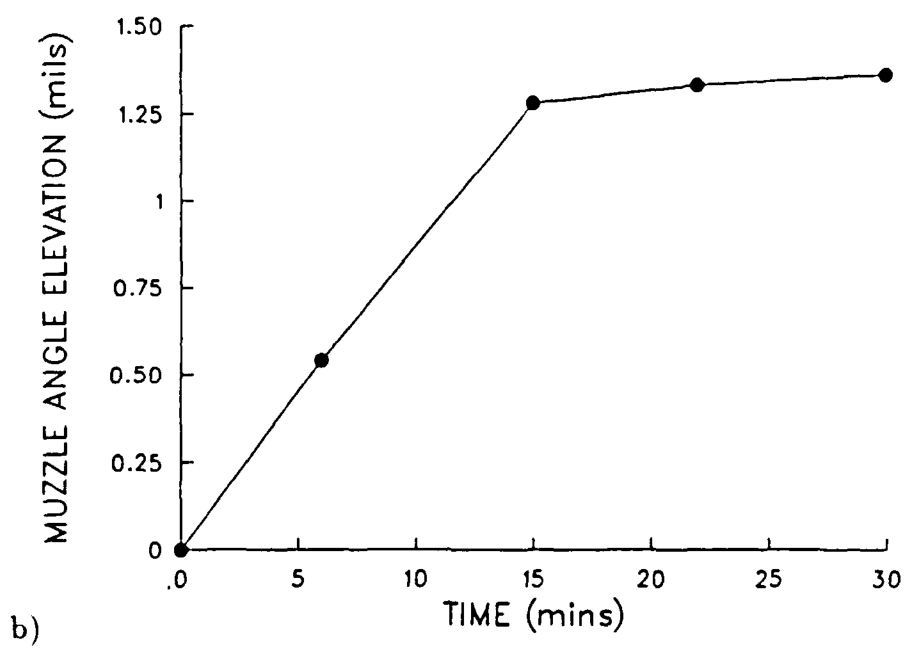
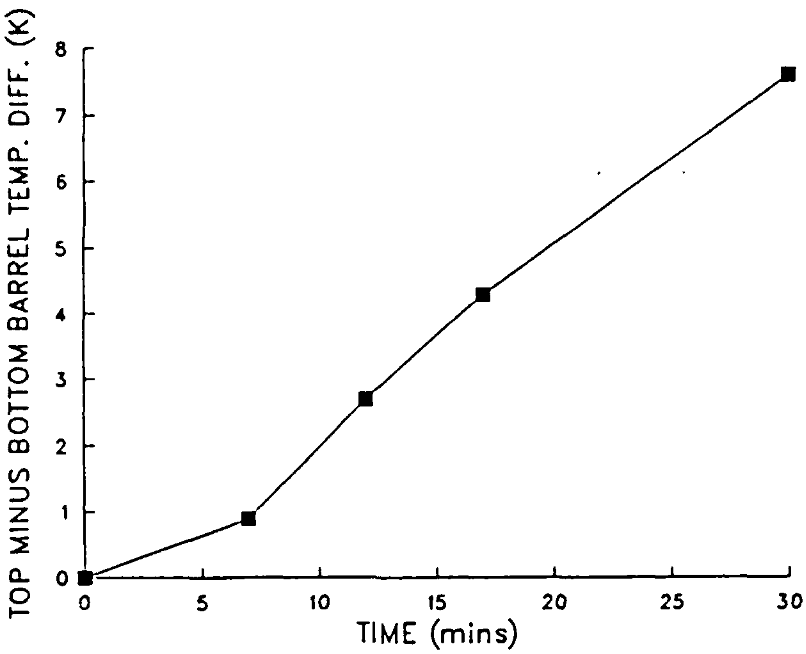


Figure 18. Effect of Heating Pad on a) Cross-Barrel Temperature Difference; and b) Muzzle Angle Deflection.



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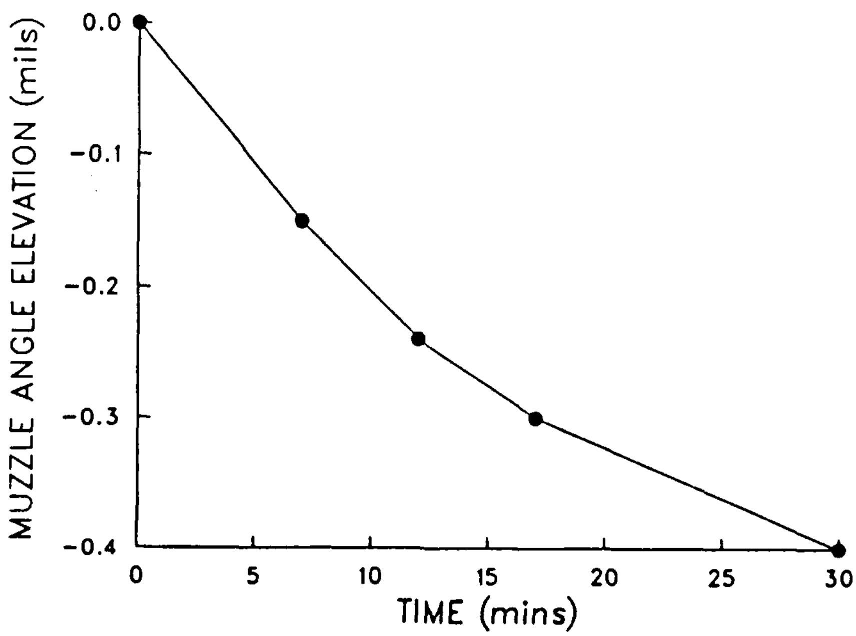

b)

Figure 19. Effect of Heating Belt on a) Cross-Barrel Temperature Difference; and b) Muzzle Angle Deflection.

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